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Review of marine renewable energies: Case study of Iran

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ABSTRACT

The objective of this paper is to briefly review the state-of-the-art in the harnessing of marine energy and study the positions and features of the boundary and domestic seas and lakes of Iran from energy point of view and the possibility of using these energy resources. Generally, the energy potentials in the seas and oceans are classified in five groups: wave energy, tidal energy, ocean thermal energy, ocean current energy, and salinity gradient energy. Due to the variety of Iran's bodies of water, other than ocean current energy, it is possible to use the rest of these energy resources. Each body of water of Iran is suitable for a specific kind of marine energy. There are great sources of tidal energy in the Persian Gulf coasts. For thermal energy, the ideal sites are located in the Caspian Sea coasts, and wave energy can economically be extracted in the Gulf of Oman coasts as well as in remote islands which are off-grid. Finally, Urmia Lake is the best location for salinity gradient energy. This study shows that more investment is required in this area for research and small scale pilot plants in order to exploit such renewable resources.

Contents

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1. Introduction

The present global energy consumption is approximately 1.6×10^7 MW, which is about 60% higher than the 1980 energy consumption [1]. Due to the rate of increase in the world population and living standard improvement in the developing countries, it is expected that this trend will continue in the future.

Thus far, this global energy demand has been met by the consumption of fossil fuels. However, in recent years as a result of the global energy crisis and problems associated with the use of fossil fuels, such as greenhouse gas emissions, a great deal of research has been carried out on renewable energies all over the world. Among these resources, the energy potentials of seas and oceans have been given much attention, because they have stored a great amount of energy in different forms, such as wave, tidal, thermal, and current energy, which can meet total worldwide electricity demand many times over [2]. Practical experience in the commercial application of sea energy, such as tidal electricity generation, has proved that, in the long term, these technologies can compete with conventional power plants [3,4]. However, financing and long term funding, especially government supports, is required before that level of commercialization can be realized.

Due to its geographical location and climatic conditions (map in Fig. 1 [5]), Iran has a marine boundary of 1259 km with the Persian Gulf, 784 km with the Gulf of Oman, and 657 km with the Caspian Sea [6]. It has also many domestic lakes, such as Urmia Lake with an area of 4867 km^2 [6]. Therefore, it seems more research is required on these resources and the possibility of economically exploiting them.

Fig. 1. Map of Iran [5].

In this paper, marine energies are classified and reviewed in five groups, namely wave energy, tidal energy, ocean thermal energy, ocean current energy, and salinity gradient energy. The energy potentials of these resources in Iran and the possibility of exploiting them are also investigated.

2. Wave energy

Waves are the most well known symbol of ocean energy. These waves are produced by wind effects on the water surface. That is why wave power is indirectly considered as a kind of solar energy. The idea of harnessing wave energy has been around for a long time. The first British patent of wave energy conversion device was registered in 1855 [7]. However, wave energy converters (WECs) were first seriously considered in the 1970s during the oil crisis [2]. Those efforts were gradually ceased due to decrease in the oil price and disappointing results of the experimental units. During the past decade, the interest in WECs has been renewed due to instability in the oil market and concerns over global warming and constraints in greenhouse gas emissions, such as the Kyoto Protocol.

2.1. Wave energy potentials

One of the most important advantages of wave energy compared to other forms of energy derived from solar energy is the high density of the wave energy. In fact, the wave energy can be considered as a concentrated form of solar and wind energies. For instance, in latitude 15°N, the average density of direct solar, wind, and wave energies are 0.17, 0.58, 8.42 kW/m^2, respectively [8]. Also, the availability of wave energy is much higher than other forms of renewable energy [2]. In addition, unlike the solar and wind energies, wave energy does not require large lands and it is more available where it is required, such as remote islands that are not connected to the grid and where the cost of electricity is usually high. Waves' predictability is another important factor to consider. While wind can be predicted only hours in advance, waves are predictable days in advance.

The amount of this energy depends on the wave length and its height. It is estimated that there is nearly 10^6 MW power in the world's waves that hit the shoreline. If open ocean waves are considered, this energy can increase to 10^7 MW [9], which is comparable with present global energy consumption. But there are different estimations on how much of this energy is exploitable. According to a realistic estimation provided by the World Energy Council, worldwide wave energy could potentially provide up to 2×10^6 MW of electricity, approximately 12% of current global demand [10]. The total wave energy resource in Europe has been estimated to be around 3.2×10^5 MW [7].

Wave energy is a combination of potential energy due to its height and kinetic energy arising from the water particle's movements. Wave energy converters can produce electricity from both forms.

The characteristics of the wave highly depend on the wind conditions, such as its speed, period, and fetch, as well as on seabed status. The average energy of a wave per unit area in deep water, where the water depth is greater than one third of the wavelength, can be estimated by the following equation [9]:

$$E = \frac{\rho g H_{m0}^2}{16} \quad (1)$$

where E is the average energy of the wave per unit area (J/m^2), ρ is the density of sea water (kg/m^3), g is the acceleration of gravity (m/s^2), and H_{m0} is the significant wave height (m). For a sinusoidal wave with amplitude of $H/2$, H_{m0} is equal to $H\sqrt{2}$. This energy is equally divided between the wave's kinetic and potential energy. For the power of a wave per unit of wave front width, the equation is [9]:

$$E = \frac{\rho g^2 T H_{m0}^2}{64\pi} \quad (2)$$

where P is the power of the wave per unit of wave front width (W/m) and T is the wave period (s).

As an example, for a wave with amplitude of 2 m and period of 9 s, wave energy and power can be calculated by Eqs. (1) and (2) to be 5 kJ/m^2 and 35 kW/m. When evaluating wave power in a certain area, it is important to find the ranges of significant wave height and period at which most wave power occurs, because these ranges should be considered as design points for the design of a WEC.

2.2. Different wave energy convertors

Wave energy application has a long history. The first patent was recorded in 1799 in France [7]. The first actual unit was constructed in 1910 in France using an oscillating water column system [11]. Since then, great numbers of systems and mechanisms have been proposed. According to the World Energy Council, the number of WEC systems under investigation around the world is approximately 100 concepts [12]. Most of these concepts are in the R&D stage, which means they require considerable time before they can be commercialized. However, there are a few systems that are mature enough to be in the pre-commercialization stage or even the early market entry level. The two leader countries in this field are Portugal and the U.K. In addition, Australia, Denmark, and Ireland are heavily investing in this sector [12].

As noted, in the 1970s there was great interest in renewable energy in general and wave energy in particular. However, this interest did not result in any system with acceptable technical and economical characteristics. One of the main reasons was ambitious targets that were set for the programs. For instance, in the U.K. the objective was to develop 2 GW wave power generation capacity by 1983. This resulted in oversize designs with very high costs [13]. Based on this experience, recently developed systems have been designed as small individual units, usually less than 500 kW, which can be installed in large numbers to generated large amounts of electricity.

These devices can be divided into three main categories: shoreline, near shore, and offshore systems. The shoreline systems require neither sophisticated mooring mechanisms nor underwater electrical cables or high pressure pipelines to transfer generated power to the shore. Their installation and maintenance are also easier. However, suitable sites to implement such plants are limited and the available wave energy in those sites is lower than offshore sites. In addition, due to unique conditions of each shoreline, most likely, the mass production and economy of scale cannot be applied to the shoreline systems, which may cause higher installation costs. The near shore systems can be helpful for coastal protection, since after wave energy is extracted, the waves are calmer and less harmful for coastal regions.

For a long time the shoreline plants attracted attentions, because they are less vulnerable to the wild nature of ocean storms. However, the real potential energy of waves can only be achieved in offshore locations. That is why the trend of progress in this industry is toward offshore locations [14], where, not only is there more power, but also much more suitable sites. Nevertheless, the reliability and accessibility of the offshore plants should be significantly improved before commercialization can be realized. It is predicted that less than 10% of the future market belongs to shoreline systems [14].

The WECs can also be identified by how they convert wave energy to the desired product. The extracted energy from waves has low velocity and high force. One method to apply this energy is to transform it to high speed rotating motion before it can be used in a generator to produce electricity. This requires a complicated mechanical system that increases capital and maintenance costs of the plant and reduces system reliability due to many moving parts, which decreases the capability of the system to withstand strong storms [15].

Moreover, the wave energy can be converted to high pressure fluid. This high pressure fluid can then be used to either generate electric power in a turbine-generator or produce desalinated water in conventional reverse osmosis (RO) membranes.

Another method, which is employed in the point absorber WEC at the Swedish wave energy research site and some others, is to use a linear generator, which is directly driven by a WEC. In such system, the heaving motion of the buoy is transformed to a permanent magnet translator, which is placed inside a stator. The heaving motion of the magnet induces electric current in the stator and produces electric power in the generator. Since in this system, no mechanical or hydraulic conversion system is required, it is mechanically less complicated; therefore, it requires less maintenance. However, due to variation in both frequency and amplitude of the generated electricity, it requires a more complex electrical system before it can be connected to the grid [15].

Based on how wave energy is extracted, the European Marine Energy Centre has classified the WECs into six main categories, namely point absorber, oscillating water column, attenuator, overtopping device, oscillating wave surge converter, and submerged pressure differential device [12,16]. Although this categorization is not exhaustive, it includes the great majority of WECs. In this work, various systems to harness wave power are identified based on the same categorization. In this section, some approaches that are deemed to be more promising are briefly presented. Then, some actual systems developed based on each approach are explained.

2.2.1. Point absorbers

One of the most commonly used approaches to exploit the wave energy at or near the water surface is using the height variation in the wave by floats. The floating part interacts with passing waves in all directions and converts wave energy to other types of energy by heaving and/or pitching motions. Depending on the mechanism used, the produced energy can be in the forms of shaft power; air or liquid pressure, which can be converted to electrical energy in shoreline or offshore facilities; or direct electricity. Also, there are proposals to use generated high pressure sea water to run reverse osmosis water desalination systems [17,18].

2.2.1.1. Wavebob. Wavebob is an axisymmetric, self-reacting WEC that converts the heaving motion of the wave to high pressure oil via a hydraulic piston pump (Fig. 2). One of the features of this machine is that its natural frequency can be set to match wave characteristics. A 1:4 scale model of this machine was installed in Ireland. The full scale of this device is expected to be 20 m in diameter and 8 m in height with the capacity of more than 500 kW [19].

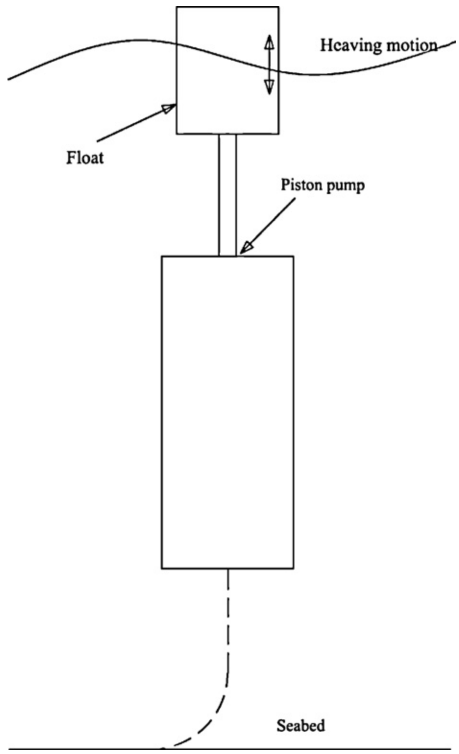

Fig. 2. Sketch of Wavebob point absorber WEC.

2.2.1.2. Poseidon (Floating Power Plant A/S). Named after the god of the sea, Poseidon is a floating hybrid system to absorb wave and wind energy. The wave energy is captured by several floats that drive a double function piston pump. The wind is captured by a standard offshore wind turbine. The system development was started in 1996 and in 2008 a 37 m wide full scale offshore model (Poseidon 37) was tested in Denmark [20].

2.2.1.3. PowerBuoy (Ocean Power Technologies). This extensively tested (for more than 24 months) WEC was developed in the United States and the capacity of its largest prototype is 40 kW [21].

2.2.1.4. Other systems. Other systems in this category that are in different levels of prototype testing and pre-commercial design are: Syncwave Systems Inc., Seabased, Ocean Power Technologies (in Canada), Finavera Renewables, and Wave Energy Technologies.

2.2.2. Oscillating water column/chamber (OWC)

Another very common concept is the oscillating water column or chamber. This system has had one of the longest development periods among WECs [22]. It consists of a partially submerged cell which is open to sea water at the bottom. When the waves pass through the system, the water column rises and falls inside the cell, acting like a piston, causing the air above the water surface to oscillate, which in turn compresses and depressurizes the enclosed air above the water column (Fig. 3). This high pressure air can then be used to run a turbine to generate electricity. The cross section of the air passage is narrowed before it enters the turbine, to accelerate the air flow and increase system efficiency. In this system, the air alternatively flows in two directions. Originally the air flow was rectified by an expensive system of check valves. This system was replaced by a Wells turbine, when it was invented by Professor Alan Wells of Queen's University Belfast in the late 1970s. The Wells turbine spins in the same direction regardless of the air stream direction due to its symmetrical blades. Disadvantages of this turbine are relatively low efficiency and poor starting characteristics [23]. There have been several other designs based on this concept [24,7].

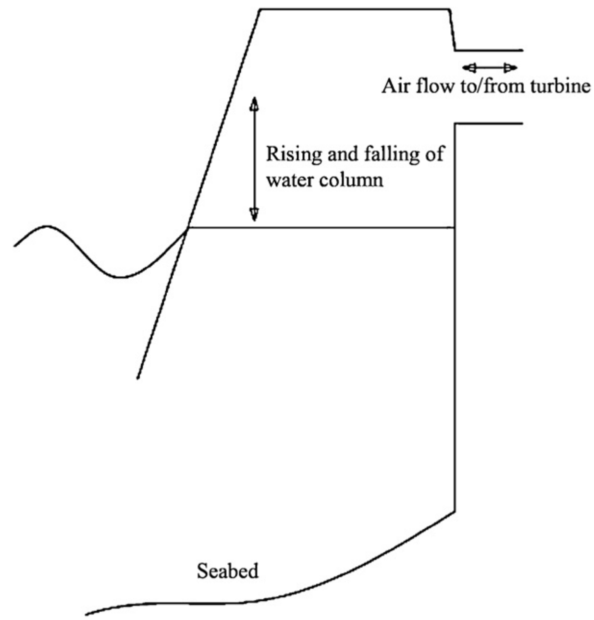

Fig. 3. Sketch of oscillating water column (OWC) wave energy convertor.

2.2.2.1. Limpet (Wavegen). One of the market leaders for this concept is a Scottish company called Wavegen. The first system designed by this firm is Limpet (Land Installed Marine Powered Energy Transformer), which was first installed on Scotland's west coast in 2000 [14]. It was a shoreline WEC with inclined oscillating water column (Fig. 3). The system was optimized for wave average energy flux of 15–25 kW/m. It employed two Wells turbogenerators with total capacity of 500 kW. This system is considered to be world's first commercial scale OWC energy plant. The company also has designed a smaller power generation module with the capacity of 18.5 kW, which can be integrated to breakwaters and coastal defenses. Wavegen has installed the world's first breakwater wave power station in Spain, which consists of 16 Wells turbines with total rated power of 300 kW. Furthermore, there is a proposal to build a 4 MW plant as a part of breakwater in Scotland [25].

2.2.2.2. Oceanlinx (formerly Energetech). The OWC system designed by this Australian company uses a high efficiency bi-directional airflow turbine with variable pitch blades, which is called the Denniss-Auld turbine. The company's first full scale prototype, called MK1, was installed in 2005 in Australia. The unique characteristic of this 500 ton system was its parabolic wall, which can concentrate wave energy into the air chamber. The system was operated for several years before it was decommissioned in 2009. Following this early system, the 1:3 scale test unit of the second generation and pre-commercial unit of the third generation of the system were designed and installed in 2007 and 2010, respectively. The latter has been successfully connected to the grid and has provided electricity since March 2010. The full scale MK3 design is expected to be rated at 2.5 MW. The Oceanlinx system has the capability to generate fresh water with some adjustments in the design by producing high pressure sea water and passing it via a RO system. It is estimated that the MK3 device will be able to produce 3 million liters of potable water per day [26]. The firm has reported a plan to install a 27 MW plant in Victoria [12].

2.2.2.3. OE Buoy (Ocean Energy). This Irish company has developed its OWC device through experiments on 1:50, 1:15, and 1:4 scale

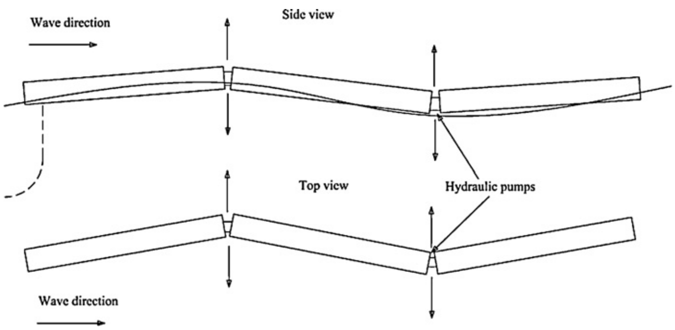

Fig. 4. Sketch of a Pelamis wave energy convertor.

models. The latter, a 28 ton machine, has survived over two years and has gained 16,000 operating hours in the Atlantic Ocean. Currently the firm is developing a 3:4 scale device, which will be followed by the construction of full scale machines [27].

2.2.2.4. OSPREY. This OWC device, developed in the U.K., has been designed to combine a WEC and an offshore wind turbine to harness wave and wind energy simultaneously [13].

2.2.2.5. Mighty Whale. This huge deep water Japanese OWC machine, with prototype dimensions of $50\,m \times 30\,m \times 12\,m$, has been designed to generate up to 110 kW in its three air chambers [28].

2.2.2.6. Other systems. There have been several other systems developed based on the OWC concept, such as Offshore Wave Energy Limited (OWEL) and Orecon. The latter is a combination of several identical OWCs on the same platform [29].

2.2.3. Attenuators

Wave energy can be exploited by the relative motion of two or more floating structures. In this system, relative yaw and/or pitch motions between sections can be used to move double-action pumps [30–32]. These machines operate parallel to the wave direction and should be able to ride the waves effectively. Since they have lower area parallel to the wave, they should resist lower forces induced by the waves [16].

2.2.3.1. Pelamis (Pelamis Wave Power, PWP). The most successful device design based on this concept is called Pelamis, developed by Pelamis Wave Power (formerly Ocean Power Delivery) in Scotland. This system is expected to be one of the market leaders in the future. It consists of several cylindrical segments. The relative motion of the segments, induced by waves, is converted to high pressure fluid by hinged joints. These joints can capture both horizontal and vertical motions of the segments (Fig. 4). This high pressure fluid can then be smoothed in accumulators to be used to drive electrical generators via hydraulic motors. The generated electricity is transmitted to shore through a seabed cable. The first full-scale grid-connected system was installed in the U.K. in 2004. The capacity of the first full-size experimental Pelamis was 750 kW, but higher capacity is expected in the future. Currently available commercial units are 4 m in diameter and 180 m in length, with about 700 ton weight [33]. The world's first grid-connected commercial attenuator WEC plant was installed off the Atlantic coastline of Portugal in 2008 by this firm. The project consisted of three Pelamis units with a total capacity of 2.25 MW. The project is expected to expand to the total capacity of 20 MW by installing additional units. Also several large scale projects are in different stages of progress, including one 3 MW WEC plant in Scotland with 4 Pelamis units, a 20 MW plant in Scotland, another wave farm in Scotland with a 7.5 MW capacity for phase 1 and up to 50 MW for phase 2, and a 750 kW plant in the European Marine Energy Centre in 2010 [33].

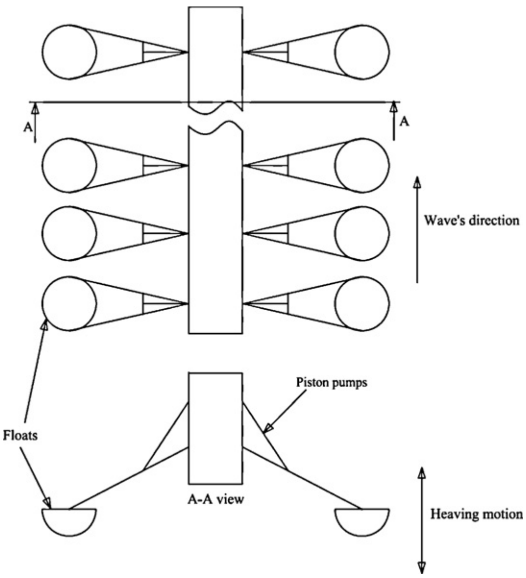

Fig. 5. Sketch of a Wave Star Energy WEC.

2.2.3.2. Wave star energy. This machine is based on a very old concept, and the first patent for this type of WEC was registered in 1898 [8]. This near shore multi-point absorption system consists of a series of hemisphere-shaped floats that are connected by arms to a central part fixed on the seabed. The heaving motion of half submerged floats is transferred to pistons by arms to compress oil into machine's common transmission system (Fig. 5). The high pressure oil drives a hydraulic motor and a generator to generate electricity. Since the system length covers several wave lengths, the wave energy can be harnessed continuously. The 5.5 kW 1:10 scale model of the system has been in operation in the sea since 2006 and is connected to Danish grid. During this period, it has been able to withstand 15 storms without any damage. A 500 kW system was installed in 2009 in the North Sea, Denmark. This 1000 ton and 40 m machine has two floats, each 5 m in diameter. The company is planning to produce its first commercial 500 kW units in 2011/2012. This system will be 70 m long with 20 floats [34].

2.2.3.3. McCabe wave pump. This machine, similar to Pelamis, makes use of the relative motion of parts for the overall system. However, in this case the hydraulic pumps are activated due to the motion of two pontoons relative to the fixed central part (Fig. 6) [7].

2.2.4. Overtopping devices

The problem with all aforementioned systems is that, because of having many movable components, they are vulnerable to the

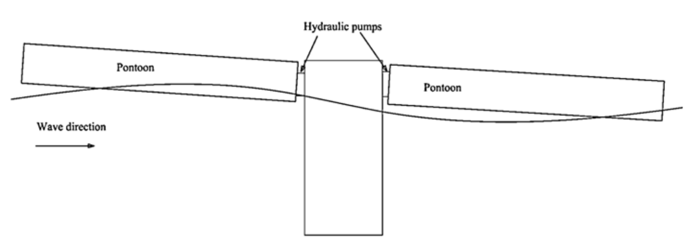

Fig. 6. Sketch of a McCabe Wave Pump wave energy convertor.

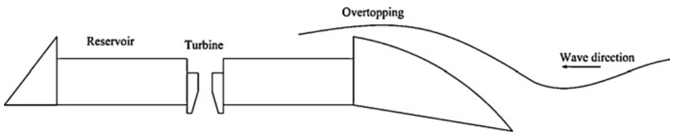

Fig. 7. Sketch of a Wave Dragon wave energy convertor.

storms. Therefore, there have been many researches on systems with minimal moveable parts. These systems can be installed onshore or offshore and can be used in all weather conditions. They can capture water from waves and hold it in a reservoir. The electricity can then be generated when water from the reservoir returns to the sea via a low-head turbine.

2.2.4.1. Wave dragon. In one of the most successful systems, called Wave Dragon, a head of hydraulic pressure is generated when sea water overtops a reservoir (Fig. 7). This system makes use of the well-proven technology employed in conventional hydro power stations. The only moving component is the turbine. The system design integrates wave reflecting wings to increase the quantity of overtopped water [35].

Its small scale 20 kW prototype pilot was the first gird-connected offshore wave power extractor, installed in Denmark in 2003 [14]. The 237 ton prototype has been successfully operated for more than 19,500 h. These units can be either shore-mounted or allowed to float offshore [36]. The proposed full-scale Wave Dragon can be 4, 7, or 11 MW in capacity. The former (4 MW) is expected to weigh approximately 54,000 ton with a 14,000 m^3 reservoir [14]. However, the system can be freely up-scaled [35].

2.2.4.2. WavePlane A/S. This design concept is similar to Wave Dragon. The main difference is that in this device there is no reservoir, and overtopped water is guided directly to the turbine. The system is designed in a V-shaped structure, where an artificial beach in front of the device is used to catch water at different elevations through various inlets which guide the water to the turbine through divided levels. The first full-scale prototype of the system was tested in 2009 [37].

2.2.4.3. Tapchan. A similar concept has been used in a shoreline system called Tapered Channel wave energy device (Tapchan). In this system, waves are guided into a gradually narrowing channel, which amplifies waves until they spill over to an above-the-sea reservoir (Fig. 8). The water stored in the reservoir can then produce electricity when it returns to the sea via a low head turbine. This system was first developed in Norway in 1985, and there has been a proposal to install a 1.1 MW plant in Indonesia [13].

2.2.5. Oscillating wave surge converters

These machines rely on extracting wave energy from wave surges and the movement of water particles.

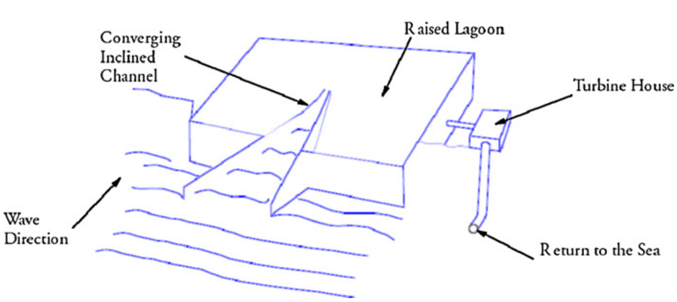

Fig. 8. Sketch of a Tapchan wave energy convertor [13].

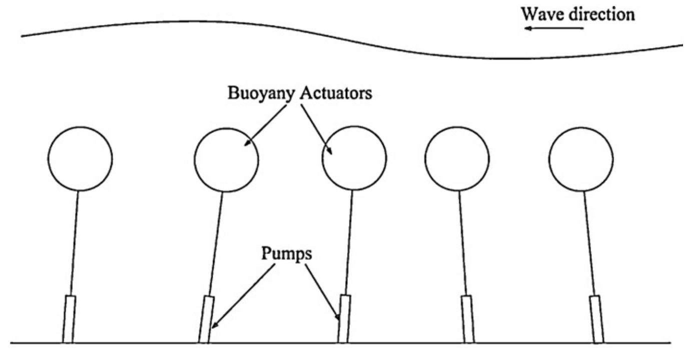

Fig. 9. Sketch of a CETO wave energy convertor.

2.2.5.1. CETO (Carnegie Wave Energy Limited). Named after a Greek sea goddess, CETO is a fully submerged and anchored array of buoys, connected to pumps that convert wave energy to pressurized seawater (Fig. 9). The high pressure seawater, at up to 1000 psi, is then transferred to shore to produce either electricity or desalinated water. The system can be operated in water deeper than 15 m, and each unit is rated at 200 kW. Being submerged provides some advantages for this device over other systems, including protection from storms, self-tuning to the wave conditions and directions, and no visual impact. The first prototype unit of this device was installed in 2003 and its first and second generations were constructed between 2006 and 2008. The commercial scale unit (CETO 3) was constructed and tested in 2009. In 2011, the company is going to demonstrate this system commercially in a 5 MW plant located in Western Australia [38].

2.2.5.2. bioWAVE (BioPower Systems). Inspired by the swaying motion of sea plants, bioWAVE ocean wave energy system captures wave energy by movement of buoyant blades as waves pass. Conceptually, it is similar to the CETO system. The devices are being developed with capacities of 250, 500, or 1000 kW. The first full scale commercial unit with capacity of 250 kW will be constructed in an Australian coastal area in 2010 [39].

2.2.5.3. WaveRoller (AW-Energy). The WaveRoller, a system developed by AW-Energy, a Finnish firm, is a series of plates anchored on seabed at a depth of about 10–25 m. The wave energy is captured by oscillation of the plate around its base, which then drives a piston pump to produce high pressure oil (Fig. 10). A 13 kW prototype machine was constructed in Portugal in 2007 followed by other systems at the same site in 2008 and in the European Marine Energy Centre in Scotland. The company is planning to build a 1 MW power plant based on the WaveRoller technology [12,40].

2.2.5.4. Pendulor. The concept of this Japanese device is similar to WaveRoller, but it is designed to be installed at the shoreline (Fig. 11) [41].

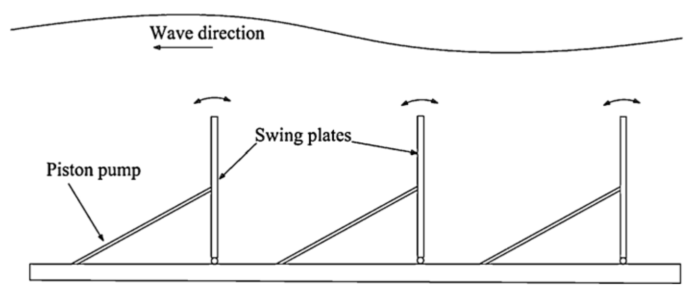

Fig. 10. Sketch of a WaveRoller wave energy convertor.

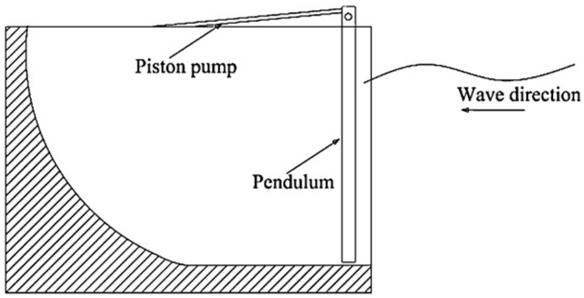

Fig. 11. Sketch of a Pendulor wave energy convertor.

2.2.5.5. Salter cam. Another proposal uses a cam (Salter cam) which vibrates due to the wave passage and can capture up to 90% of the wave energy [42,8].

2.2.6. Submerged pressure differential converters

The rise and fall of water level due to waves can create a differential pressure at the seabed. The devices based on the submerged pressure differential make use of this gradient to pump fluid through a system to generate electricity. They are typically installed near shore on the seabed.

2.2.6.1. Archimedes Wave Swing (AWS Ocean Energy). This machine is installed on the seabed, and consists of a large air tank (10–20 m diameter) with a flexible upper section. The wave motions create variable pressure, which in turn causes the upper section of the take to move up and down and create high pressure air flow. A 1:20 scale model was successfully tested in Portugal in 2004, and the design of the third generation of the system with a capacity of 2.4 MW and 4 MW has been developed [43].

2.2.7. Other wave energy converters

Some of the existing devices cannot be fitted to aforementioned categorizations. Also, newer ideas to extract wave energy are being proposed from time to time [44], for instance, a specially designed turbine that is turned directly by the waves (Wave Rotor) and flexible structures that changes shape/volume [16].

2.3. Challenges of wave energy and environmental effects

The main issue with development of wave energy is its high cost. This requires support from governments, including funding for research, financing large scale demonstrations, and providing subsidies and guaranteed purchase price, until the industry is mature and can compete with conventional power generation technologies. For instance, one of the reasons that helped Portugal to be a leader in this field is the guaranteed electricity price of €0.235/kWh for the first 20 MW of power generation [14]. In order to reduce WEC cost, these systems need more demonstrations to gain the needed real-world practical experience in installation, operation, and maintenance.

In terms of environmental impacts, a few short-term studies on the effects of installation of WEC systems on the environment suggested that these systems have minimal negative effects on the ecosystem of the installation sites. One of these studies [15] shows that neither species abundance nor biodiversity is reduced in the region after installation of the system. There were also positive signs that the area could recover after disturbance during construction, even with ongoing research activities. Moreover, there was not any concern about extinction of local marine organisms. However, long-term environmental analysis is required to evaluate impacts of these systems.

Some methods are being tested to improve environmental performance of the WECs. For instance, in the Swedish wave energy research centre, the differences between the concrete foundation with and without holes have been investigated. The idea was that the holes could provide shelter for many marine mobile species, and could have a positive impact on colonizing species [15].

2.4. Test facilities

Recently, several research facilities have been established to promote wave energy research and development around the world, especially in Europe.

The Swedish wave energy research area is located 2 km offshore, on the Swedish West coast and covers 40,000 m^2 area. The project was commissioned in 2004 and would continue until 2014. The objective is to install 10 grid-connected wave energy converters, 30 buoys to study environmental impacts of the wave energy converters, and a surveillance tower to monitor the interaction between waves and converters. The wave energy converters are connected to a measuring station onshore via a sea cable, which in turn is connected to the grid. The average energy flux of the site was 3.4 kW/m in 2007 [15].

A similar test facility, called Pilot Zone, was established in Portugal, 150 km north of Lisbon in 2008. The objective of this 400 km^2 site is to promote and support R&D for wave energy. This facility will be connected to both the local and national network [12].

The European Marine Energy Centre (EMEC) is a research centre established in 2001 to facilitate full-scale grid-connected prototype wave and tidal energy conversion devices. It is located in the U.K. and exposed to the North Atlantic Ocean's powerful waves. It can test deep water (50 m depth) as well as shallow water machines. Some of the systems that have already been installed or are expected to be installed soon are as follows: Pelamis (Pelamis Wave Power, PWP), AW Energy, Oyster (Aquamarine Power Ltd.), and PowerBuoy (Ocean Power Technologies) [16].

Similarly, another offshore test facility in the U.K., called Wave Hub, can accommodate four different systems at any time in a pre-commercial environment. Each device will be given 2 km^2 area with grid-connected electricity generation capacity of maximum 4–5 MW for approximately five years [45]. The first four companies to install their systems, starting in 2010 have been selected: Oceanlinx, Ocean Power Technologies, Fred. Olsen, and WestWave (using a Pelamis device) [12]. It is expected that in future up to 30 devices can be tested at this facility.

2.5. Wave energy potentials in Iran

The first and the most important parameter that should be considered in selecting a site for a wave energy power plant is wave potential power. This energy is directly proportional to the square of significant wave height and its period, as shown in Equation 2. In order to determine the wave characteristics, usually the average wave data for a certain period of time is required. This can be performed by collecting the data from each selected site. In Iran, except for a couple of places and for a very limited time, such data were not available. Due to the fact that waves are produced as a result of interaction of wind and the surface of sea water, wind data can be used to predict the wave's characteristics. Wind data have been recorded and have been available for a much longer period of time in Iran. Therefore, the recorded wind data from 1986 to 1995 for 14 sites from both the northern and southern coasts have been collected and used to estimate the wave characteristics. Table 1 shows the power per meter of the coast line, total length of the coast, and total power of these sites based on the data provided by the Renewable Energy Office, Deputy of Energy Ministry of Iran

Table 1
Potential wave power in selected sites in Iran's northern and southern coasts based on the data provided by the Renewable Energy Office, Deputy of Energy Ministry of Iran [46,47].

Site name	Power per meter of coast (kW/m)	Coast length (km)	Total power (MW)
Abadan	2.9	34	101
Abomosa	5.1	5	26
Anzali	3.4	124	423
Astara	0.6	83	50
Babolsar	2.2	155	341
Bandar Abbas	0.9	232	210
Lenge	3.4	359	1222
Bousher	2.2	474	1045
Chabahar	5.8	265	1539
Jask	3.2	289	925
Mahshahr	1.7	223	380
Noushahr	1.1	99	110
Ramsar	1.4	100	141
Siri	5.3	5	27
Total			6540

[46,47]. As Table 1 shows, 265 km of Chabahar coast with 5.8 kW power per meter of coast and total power of 1539 MW is the best site in terms of wave energy potential. This is expected because this site is in the coast of the Gulf of Oman, which is connected to the Indian Ocean, where the average wave power is between 10 and 15 kW/m [13,48].

In Table 2, the average and maximum wave power potentials in the Iranian coasts [46,47] are compared with a few other countries and the world average [8,13,18]. As Table 2 shows, in the Persian Gulf islands there is considerable wave energy potential. Since these islands are not connected to the national grid, the wave energy converters can be economically operated as distributed electricity generators.

3. Tidal energy

Tidal energy is one of the most available energies of seas. Unlike most of the other renewable energies, which directly or indirectly are derived from solar energy, this energy is created by the gravitational forces of the Moon and the Sun on waters of the Earth and the rotation of the Earth. One of the advantages offered by tidal energy over solar and wind energy is its predictability. It is estimated that there are around 100 GW of tidal power in the world bodies of water, of which only a fraction is exploitable because it occurs in the gulfs and estuaries [2]. The leading countries in harnessing tidal energy are Canada, France, the U.K., and the U.S.A. [12].

Basically, the tidal energy can be in forms of either potential energy of water level difference during ebb and flood or kinetic energy of tidal current, which are briefly explained in the following sections.

Table 2
Comparison of average and maximum wave energy in Iran and other parts of the world [46,47,8,13,18].

Site name	Average power (kW/m)	Max. power (kW/m)
Persian Gulf islands	16.6	19.0
Persian Gulf coasts	3.5	6.1
Gulf of Oman coasts	10.5	12.6
Caspian Sea coasts	3.2	6.7
Japan	7.0	12.5
New Zealand	23.6	100.0
Western Europe	46.9	70.0
World (average)	9.0	–

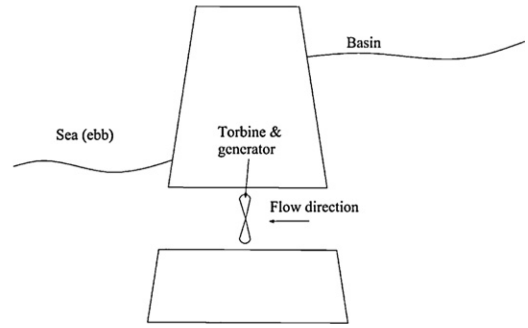

Fig. 12. Sketch of a single-pool ebb system.

3.1. Tidal potential energy extraction

In the modern systems, tidal potential energy is extracted by constructing a barrage against sea water and using the height difference of the sea water and the water behind the barrage, caused by tides, to operate turbines installed in the barrage wall. The power that a tidal power generation plant can produce depends on both the tidal range and the capacity of the basin. The tidal energy is directly proportional to the square of the tidal range. This difference is almost 1 m in open oceans. But in coastal areas, it depends on shore conditions and can be as high as 16 m. Also, with higher capacity of the pool, available energy will be increased. Furthermore, if the basins are large enough, the problem of interrupted electricity generation can be partially solved by proper arrangement of the pools. In addition, there are other factors to consider, like the distance of the site to the electricity grid, the current application of the basin, and distance from sea waves and storms.

Tidal power has been around since at least tenth century and was used to move mills in England, France, and several other countries. Although there have been many modern designs and/or experimental pilot projects to harvest tidal energy, to the authors' best knowledge, only four commercial tidal electricity generation plants have been constructed in the world. The Rance Tidal Power Station in France is the world's first and largest tidal power plant with the capacity of 240 MW and the annual output of 600 GWh and it has been operating since 1966 [3,49]. North America's only tidal power plant, the Annapolis Royal Generating Station with the capacity of 20 MW and the annual output of 30 GWh, was opened in Nova Scotia, Canada in 1984 [50]. Also, two small tidal plants were installed in Russia and China with the capacity of 400 and 500 kW in 1968 and 1966, respectively [51].

The concept of utilization of tidal potential energy is similar to the hydro dams, where electricity is generated by static pressure of water. However, unlike hydro dams, due to different possibilities for flow direction in turbines, several different schemes have been employed or proposed for exploiting energy from the tides [51]. These schemes are categorized as follows:

1- single-pool ebb system;
2- single-pool flood system;
3- single-pool two-way operation system;
4- two-pool ebb and flood tide system;
5- two-pool one-way system (high and low pools).

In the first design, the basin is filled during the flood through the gates. When the basin is full, the gates are closed until the desired water head is created due to fall in sea level. Then, the basin is emptied by water flowing through turbines which in turn generates electricity (Fig. 12). This method has been used in tidal mills for a long time, and some of them are still operational. The same scheme has been employed in the Annapolis Royal Tidal Power

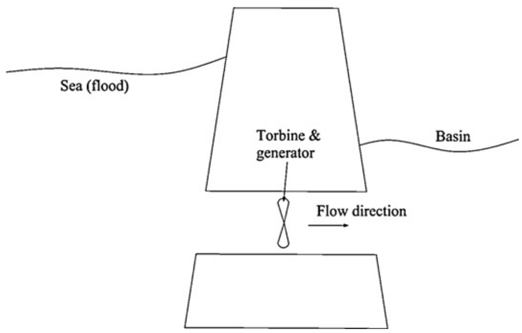

Fig. 13. Sketch of a single-pool flood system.

Generating Station. In this plant, the minimum required water head is 1.6 m. When this head is available, approximately 400 m^3/s of water flow passes through turbine. The plant generates electricity for five hours and then it is off for seven hours [50].

The system and mechanism for the second scheme is similar to the first one. The only difference is that the water flows through the turbine when the basin is filling (Fig. 13). The efficiency of this scheme is much lower than that of the first one.

In the third scheme, by taking advantage of a bi-directional turbine, electricity can be generated both when the water flows into the pool at flood and when it flows out of the pool at ebb.

This method has been successfully employed in the Rance Tidal Power Station. At this power plant, the amplitude between low and high tides can reach up to 13.5 m. A 750 m structure was constructed to block a 22 km^2 area with the capacity of 180 million m^3 of sea water. Twenty four specially designed bulb sets (also known as axial flow turbines) were used, each unit with a capacity of 10 MW. Although the capital costs of this plant were high, the overall average cost of electricity has been lower than Electricite de France's (EDF) average generation costs [3,49].

One of the features of this power station is that when the high pool is nearly full, additional water can be pumped into it using excess electricity in the grid [49]. This water pumped in at a few meters of head later falls through a much larger head generating energy and returns several times the energy required for pumping. This also increases system flexibility to meet the requirements of the network.

In Scheme 4, a combination of Scheme 1 and Scheme 2 is used, where one of the two pools operates based on the single-pool ebb system and the other one based on the single-pool flood system.

The fifth scheme requires two pools, high and low, physically adjacent. The high pool is filled each high tide and the low pool is emptied each low tide. Electricity is generated when water flows from the high pool to the low pool through the turbine (Fig. 14). This type of tidal power station can generate electricity almost continuously and has high flexibility in generation time.

It should be noted that using the aforementioned systems has significant barriers. Firstly, these methods require a river estuary or a bay with extremely high tidal range. The sites with such a high tidal range are very limited. Also, the ecosystem in the river estuaries is very sensitive and constructing a barrage to exploit tidal

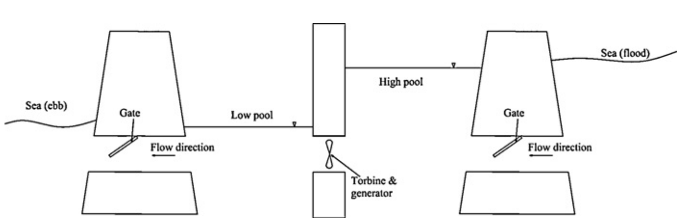

Fig. 14. Sketch of a two-pool one-way system.

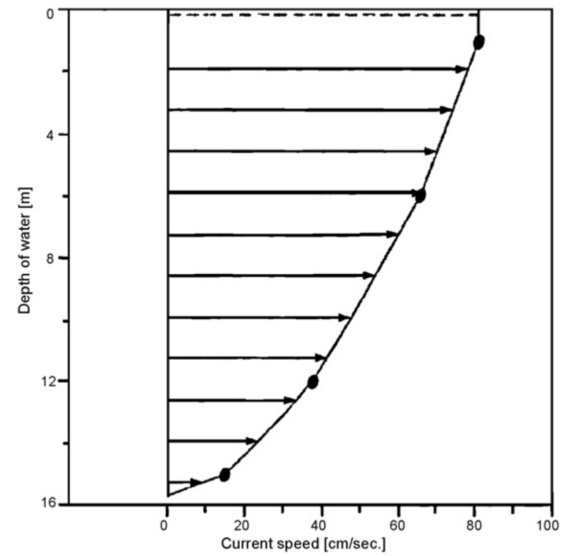

Fig. 15. A sample profile of tidal current velocity [52].

energy may cause considerable negative impacts on the environment. Another problem with tidal power generation that should be considered is that the neap tidal range is about one third of the tidal range of average spring tides. At the Rance River tidal power plant, the electricity generated during neap tides is only 80,000 MWh/day, compared to 1,450,000 MWh/day during an equinoctial spring tide, a ratio of 18:1, which causes a disturbance in the grid control [3].

Therefore, researchers and developers are currently focusing on the kinetic energy of tidal current by investigating tidal generated coastal currents.

3.2. Tidal potential energy extraction

The tidal stream generators, in principle, are similar to wind turbines. But because of the much higher density of water in comparison to air, they can operate with much lower current velocity. Most suitable sites to harvest tidal current power are located in water depths of 20–30 m which are about 1 km from shore, especially suited to remote and island communities [14]. In these sites, tidal current speed is magnified by topographical features, such as the shape of the seabed and a narrow channel. Since the kinetic energy of tidal currents is directly proportional to the square of the current speed, it is essential to measure and analyze this speed to evaluate the suitability of candidate sites. In the tidal current energy evaluation, the variation of current velocities during a tidal cycle, which is strongest in the middle of the cycle, should be considered. In addition, the neap and spring tidal current velocities can be varied considerably. It should be noted that in shallow water some of tidal current energy can be lost due to bottom fraction. Fig. 15 illustrates a sample profile of tidal current velocity [52].

The tidal current energy convertors can be divided into three main categories: horizontal axis turbine, vertical axis turbine, and oscillating hydrofoil. These systems can be either fixed to a seabed mounted structure or floating. In the former systems, the turbine can be supported by a gravity structure or can be mounted on a pile penetrating into the seabed (similar to a conventional wind turbine) [16]. The floating systems can be either fixed or flexible. The flexible mechanisms enjoy an advantage of being self-aligned to the tidal current direction.

3.2.1. Horizontal axis turbines

In these devices, the rotational axis of the turbine is parallel to the current stream (axial-flow turbine) and it consists of several

blades mounted on a rotor. The rotational power extracted from tidal current is transferred to a generator via a gearbox to generate electricity. This type of tidal energy convertor can be housed in a duct, like Venturi, to concentrate stream and increase current speed. Several devices have been developed based on this concept, which are briefly explained in this section.

3.2.1.1. Open centre turbine. Developed by the Irish firm OpenHydro, this turbine has been deployed by Nova Scotia Power, Canada, in the In-Stream Tidal Turbine Project. The first full scale prototype 1 MW unit of this type of turbine was installed in 2009 and two more are planned to be installed in 2010. The turbine and its base, a 400 ton subsea structure, are 16 m in diameter and can produce energy in both directions [53]. The design includes several features, such as a large open centre turbine designed to provide a safe passage for marine life, to be free of oil, grease, and other lubricating fluid, and to have very low levels of mechanical noise, to ensure minimal impacts on marine life. However, the plant will be tested for one to two years to monitor its environmental impacts before further expansion can be made [53].

3.2.1.2. Free flow turbine. This North American system was developed in the U.S.A. and Canada by Verdant Power Ltd. A three-bladed prototype of the machine was installed in the East River in New York City. It is grid-connected and can generate approximately 40 kW power. The next generation of the system is expected to be installed in 2010/2011 [54].

3.2.1.3. DeltaStream Turbine. A 1.2 MW system, developed by a firm in the U.K. called Tidal Energy, has three blades with total diameter of 15 m [55,51].

3.2.1.4. Evopod Tidal Turbine. Developed by a company in the U.K. (Ocean Flow Energy), this floating device consists of five blades. The mooring system of this machine allows an optimal orientation to tidal current direction [56,51].

3.2.1.5. Lunar Energy Tidal Turbine. In this design a turbine with 11.5 m diameter, is housed in a 15 m diameter and 19 m long duct. This bi-directional device can generate 1 MW power and has been developed in the U.K. [57,51].

3.2.1.6. Other systems. The horizontal axis turbines are the most popular approach to harness tidal current energy. Some other devices that have been developed based on this concept are as follows: Neptune Tidal Stream Device (2.4 MW) [58], Nereus and Solon Tidal Turbines (500 kW) [51], SeaGen (1.2 MW) [59], TidEl Stream Generator (500 kW), and Tidal Stream Turbine (300 kW) [60].

3.2.2. Vertical axis turbines

The rotational axis of these devices is vertical and perpendicular to the tidal current stream. A few devices that have been developed based on this concept are as follows.

3.2.2.1. Tidal Fence Davis Hydro Turbine. Developed by a Canadian company called Blue Energy, this device makes use of the Davis Hydro Turbine with four blades rotating around a vertical axis. It is reported that this machine can be constructed in a wide range of capacities, from 5 kW to 500 kW in the river application to 200 MW to 2000 MW in the tidal current application. However, no prototype of the system has been constructed or tested yet [61,51].

3.2.2.2. Gorlov Helical Turbine. This vertical axis tidal current convertor was developed by GCK Technology in the U.S.A. and consists of three helix shaped twisted blades [62].

3.2.3. Oscillating hydrofoils

In this concept, the tidal current causes oscillating motion in a hydrofoil connected to an arm. This motion can be converted to hydraulic pressure, which in turn can generate electricity. A few devices developed based on this technology are as follows [16].

3.2.3.1. Pulse Tidal Hydrofoil. This device was developed by Pulse Generation, a firm based in the U.K., and can be installed in shallow water. It operates based on a horizontal hydrofoil that sweeps up and down to produce oscillating motion [63].

3.2.3.2. Other systems. The Stingray Tidal Energy [51] and bioSTREAM [64] are two other devices that were designed based on this technology.

3.3. Tidal energy potentials in Iran

Due to the fact that there is no tide in the Caspian Sea in the northern part of the country, this study focuses on the southern coasts, the Persian Gulf and Gulf of Oman.

In order to use tidal kinetic energy, the current speed of between 2 and 3 m/s is required [2,51]. A current speed of lower than 2 m/s does not have significant energy and it is not economical to extract this energy. A current speed of higher than 3 m/s, on the other hand, can be destructive for turbines [2]. An energy flux of a tidal current with the speed of 3 m/s is approximately 14 kW/m^2 [65].

The tidal current energy of the southern coasts of Iran is negligible since the maximum velocity of the current is 0.5 m/s [6]. Therefore, in this work the potential energy of the water level difference between ebb and flood is studied.

The required conditions for economic power generation from tidal potential energy include a high tidal range and a basin having with a narrow enough mouth so that it can be dammed and deep enough so that turbines can be set below the level of the low tide. Thus, these parameters were investigated in this study.

In order to perform the analysis in Iran, 36 most suitable sites in terms of tidal potential energy were selected. In these sites, average annual potential energy due to water level difference between ebb and flood was estimated based on the data provided by Renewable Energy Office, Deputy of Energy Ministry of Iran [46,47]. Table 3 illustrates tidal range, tidal potential energy, basin area, and length of required barrage for some of the investigated sites.

Among these sites, Mahshaher, Alvandroud, and Khormosa entrance with tidal range of 3.9, 2.6, and 2.5 m, respectively, were determined to be the best sites. Since existing pool size has a great impact on the tidal potential energy, the sites with basin bigger than 1 km^2 are listed in Table 3 with related data for each site.

In order to estimate the tidal power generation potential in Table 3, many parameters were considered. However, the potential energy of the tidal system in each tidal cycle (one ebb and one flood) can be simplified and estimated by Equation 3 [66].

$$E = \eta \times \rho \times g \times h \times q \tag{3}$$

where E is the potential energy of the tidal system in each tidal cycle (J/cycle), η is the efficiency of the system (hydro turbine), ρ is the density of sea water (kg/m^3), g is the acceleration of gravity (m/s^2), h is the mean level difference between water in the basin and sea (m), and q is the flow rate of sea water that flows through the turbine at each cycle.

It should be noted that Equation 3 should be applied each time the basin is filled or emptied through the turbine and power is generated. For instance, in the first scheme, the water goes through the turbine only when the basin is emptied, but in the third scheme, power is generated in both directions. In this analysis, the first scheme is considered.

Table 3
Characteristics of suitable sites to construct tidal power plants in the Iranian coasts in the Persian Gulf and Gulf of Oman based on the data provided by Renewable Energy Office, Deputy of Energy Ministry of Iran [46,47].

Site name	Nearest site with data available	Basin area (km^2)	Tidal range (m)	Potential (MW)	Barrage length (m)	Notes
Rig Port	Khark Island	10.5	1.4	3	500–700	Muddy pool
Shif Island	Khark Island	19.0	1.4	4	1000–2500	
Rig Port	Khark Island	17.5	1.4	4	700–1500	Muddy pool
Chark Port	Farour Island	2.5	1.4	1	100	Muddy pool
Asaloie Port	Kangan	50.0	1.4	12	7000	
Gatan	Jask Gulf	1.5	1.8	1	300	
Kerian	Rajaei	13.5	2.3	8	2500	
Kerian	Rajaei	2.5	2.3	2	750	Muddy pool
Banzarak	Rajaei	2.0	2.3	1	120	
Banzarak	Rajaei	1.2	2.3	1	100	
Tore	Arvandroud	35.0	2.6	28	800	
Choibadeh	Arvandroud	12.0	2.6	9	500	[a]
Darak	Galak	7.5	2.1	4	500	[a]
Gabrik	Jask Gulf	1.7	1.8	1	100	Muddy pool
Gabrik	Jask Gulf	1.7	1.8	1	120	
Yekdar	Jask Gulf	2.2	1.8	1	200	
Chabahar	Chabahar	4.2	1.8	2	500–800	
Gachin	Hengam	3.8	1.8	2	500	
Khormosa	Khormosa	13.0	2.5	9	600	
Mahshahr port	Mahshahr	170	3.9	301	1200	
Khorsalag	Khormosa	17.0	2.5	12	400–600	
Arzani	Sirik	2.5	2.3	2	500	

[a] The Bahman Shir river connection should be blocked.

In order to estimate E, first, it is assumed that the efficiency of the system is 100%; that means the result of this calculation is maximum available potential power and not actual exploitable power. The flow rate of sea water that flows through the turbine at each cycle of ebb and flood in the simple case when the basin area is uniform during high and low tides can be calculated using Equation 4:

$$q = A \times H \tag{4}$$

where A is the area of the barrage basin (m^2) and H is the maximum tidal range (m).

And finally, the average tidal range is equal to half of the maximum tidal range, $h = H/2$. This is due to the fact that as the flow passes through the turbine, the difference between water in the basin and at sea level reduces. Therefore, there is less hydraulic head available for the turbine.

As an example, the calculation for Mahshahr port is presented in this section. According to Table 3, the basin area (A) of this site is 170 km^2 and the tide range (H) is 3.9 m. Thus, the basin capacity and the average tidal range can be estimated as follows:

$$q = A \times H = 170\,(\mathrm{km}^2) \times 3.9\,(\mathrm{m}) = 6.63 \times 10^8\,(\mathrm{m}^3)$$
$$h = \frac{H}{2} = \frac{3.9}{2} = 1.95\,(\mathrm{m})$$

Now, the tidal power generation potential can be estimated by using Eq. (3), as follows:

$$\begin{aligned} E &= \eta \times \rho \times g \times h \times q \\ &= 1 \times 1025\,(\mathrm{kg/m^3}) \times 9.8\,(\mathrm{m/s^2}) \times 1.95\,(\mathrm{m}) \times 6.63 \times 10^8\,(\mathrm{km^3}) \\ &= 1.3 \times 10^{13}\,(\mathrm{J/cycle}) \end{aligned}$$

Since there are two complete cycles of high and low tides everyday, total potential energy per day is equal to 2.6×10^7 MJ/day. Then, the mean tidal power generation potential can be estimated as follows:

$$\text{Power generation potential} = 2.6 \times 10^7 \left(\frac{\mathrm{MJ}}{\mathrm{day}}\right) = \frac{2.6 \times 10^7}{86400}(\mathrm{MW}) = 301\,(\mathrm{MW})$$

As noted earlier, this is the simplest estimation with several assumptions. This is a good method to obtain some rough estimations of the tidal power generation potential, especially for the sites with relatively large basins. But the numbers in Table 3 were calculated more accurately by considering the actual conditions for each specific site.

As Table 3 shows, there are various sites with a wide range of characteristics. The basin area can be in the range of 1.2–170 km^2. The tidal range and length of required barrage can be as low as 1.4 m and 100 m or as high as 3.9 m and 7000 m, respectively. Mahshahr port has the largest basin and strongest tides; therefore, it is the most suitable site for tidal energy extraction with 301 MW tidal power generation potential. It is obvious that the final decision should be made based on more detailed data and investigation.

The tidal power plants can be operated in either grid-tied or off-grid modes. In Iran, they can be connected to the grid, since almost all sites listed in Table 3 are near grid lines. Therefore, the selection of plant configuration and operation conditions of these power plants depends on grid requirements, either peak load or base load. If these power plants are operated as peak load electricity producers, the best scheme is a two-pool one-way system (Scheme 5) with flexible power generation time. Also, during off peak hours water can be pumped to store energy and produce more power later when needed most.

For Iran, it seems that the simplest and most economical scheme is the single-pool ebb tide system (first scheme), because it requires less hydro-mechanical equipment and the turbine is simpler. On the other hand, since Iran's dam construction industry has improved considerably during the 90s, tidal power plants can be developed mainly based on the domestic technology and resources.

In order to continue this study, two actions should be taken. First, at the top sites presented in Table 3, more detail and extensive feasibility studies should be performed to select the best site(s). Then, after some modeling, a small scale tidal power plant should be constructed as a pilot case study to gain some insight operational experience and to assess and evaluate effectiveness of the systems.

4. Thermal energy

About 70% of the solar energy reaching to the earth is absorbed by oceans [67]. This causes the ocean surface water to be warmer than that at the bottom. Since the process of collecting and storing

of this energy is free here, it could be cheaper than other approaches to the use of solar energy. On the other hand, because the sea water temperature at night, day and in different seasons varies only slightly, this energy is more stable than the other forms of solar energy and can be used as a base load power generation system. In total, it is estimated that about 10^7 MW power, more than 60% of the current global energy demand, could be provided by ocean thermal energy conversion (OTEC) systems, without affecting the thermal structure of the ocean [68,2,69].

The most important parameter in application of this energy is the temperature difference between the surface and the deep water. At 1000 m depth, the water temperature can reduce by as much as 20 °C. The essence of using this energy is to operate a thermal engine between this heat sink and source to generate power. Due to the small temperature difference between the warm and cold water, the efficiency of such an engine is very low. For instance, if the temperature difference is considered to be 20 °C, ideal cycle (Carnot cycle) efficiency can vary from about 6% to 7%. The actual efficiency of a real system could be around 3% [70]. Thus, a high rate of flow is required to produce a reasonable amount of energy. Therefore, for a temperature difference of less than 20 °C, this energy cannot be considered, since the required energy for pumping the water is more than the equivalent electrical energy produced. In addition, the depth at which cold water is available should be considered, because this water must be pumped to the surface to be used. Usually less than 1000 m is a suitable depth [12,2]. In fact, there are two methods to bring cold deep seawater to the surface. The water can be pumped or it can be desalinated at the sea bottom. Since the density of desalinated water is lower, it will float up to the surface automatically.

The other important factor is the distance of this deep water to the coast. Since the produced electricity should be transferred to the coast, this distance should be as short as possible. Alternatively, the plant can be located on the coast. In this case, cold and warm water should be transferred to the plant. Also, the plant's output can be used to produce hydrogen or other fuels which can be transferred to the shore. In all these cases, the distance of the deep water to the shore is an important parameter. Furthermore, there are other factors like tide and storm impacts, and ship movement patterns in the area that should be considered.

The OTEC systems have some extra positive attributes, like potable water production, application of output cold water for air conditioning systems, application of the nutrient-rich water in aquaculture to raise seafood, and mineral extraction. Furthermore, commercial fishing is expected to benefit. Cool water from the depths of the ocean is rich in nutrients and living organisms (plankton) and when brought to the surface, would attract a wide range of sea life. However, there are some concerns about ecological effects of the OTEC [2].

The first attempts to exploit ocean thermal energy were started in the 1800s. The first plant was proposed in 1881 and a 22 kW plant was constructed in 1930 [71]. Since then, several plants have been proposed and some of them were actually built as pilot plants. Currently, the U.S.A., India, Cuba, and Indonesia are actively involved in the development of this technology. In the United States, there have been several designs of OTEC, from 1 MW to 100 MW, at the various stages of development. It is expected that some of these plants will be installed in 2011. It has been also reported that a 1 MW floating OTEC pilot plant was installed in India in 2008 [12].

These plants based on their location are categorized as floating, land based, or shelf based plants. They can be also categorized based on the operating system, closed or open cycles. The main difference between open and closed cycle is their operating fluid. In a closed cycle, a low boiling point fluid, like ammonia, is used in a Rankine cycle. On the other hand, in an open cycle, the sea's warm surface water is evaporated in a low-pressure vessel (vacuum chamber) and used as working fluid. The main advantage of the latter system is the production of drinking water at the end of the cycle. In addition, closed and open cycles can be integrated to form hybrid cycles.

4.1. Sea thermal energy potentials in Iran

The Persian Gulf is one of the hottest seas in the Middle East and its surface temperature is about 30 °C in August. However, due to the depth of this sea, which is about 30–182 m, the required cold water to be obtained from the depths is not available. Therefore, it is expected that these systems cannot be applied in the Persian Gulf. There is not enough reliable data in this case to present a final scenario. In order to perform such an analysis, the profile of water temperature versus depth must be obtained.

Like the Persian Gulf, there are no reliable data to create a profile of water temperature versus depth in the Gulf of Oman. However, because of the availability of deep water and direct connection of this sea to the Indian Ocean, which is one of the most suitable places to use OTEC, it is expected that there are considerable potentials in this body of water. Due to the fact that in the southeast of Iran there is a shortage of potable water (especially in Sistan and Balouchestan province), the open cycle is the best choice in order to produce electricity and potable water simultaneously.

On the other hand, the Caspian Sea is one of the most suitable places to use the sea thermal energy. In this area, the temperature difference between surface and depth is more than 20 °C in 7–8 months of the year and in the rest of the year the temperature difference is between 10 and 20 °C [6]. This temperature difference can be found between the surface and a depth of 100 m whereas even in equatorial regions the same difference is found between the surface and about 1000 m [12]. Also, the deepest point of the Caspian Sea is on its southern Persian side and the distance of the iso-depth lines of 300–400 m do not exceed 20 km from Iran's coast [6], and also few storms and lack of tides in this sea are other advantages. Due to the fact that in the northern part of Iran there are plenty of water sources, a closed cycle is more suitable.

There are many sites in this area where an OTEC system can be implemented. In fact, every point where water depth exceeds 200 m is satisfactory. However, the hydrographical plots show that the Gilan province, especially sites between Noshahr and Chaloos, are suitable for the use of this sea's thermal energy.

There have been some conceptual designs for thermal energy conversion for the Caspian Sea [72]. In these designs, two units of 1 MW and 10 MW open cycle and two units of 0.5 MW and 50 MW closed cycle were investigated. For these units, the warm water temperature was 27 °C and the cold water (at a depth of 100 m) was 7 °C. In the 1 MW open cycle, the warm and cold water flow rates were 3975 m^3/s and 2932 m^3/s, respectively. The net power output of the generator and system were 1.8 MW and 1.05 MW, respectively. The corresponding data for the 10 MW open cycle unit were 30,930 m^3/s, 22,810 m^3/s and 14 MW, 8.7 MW, respectively. The efficiency and potable water production rate for the 1 and 10 MW open cycle units were 2.2%, 2.4% and 19.7 kg/s, 154 kg/s, respectively. In the ammonia based closed cycle under the same operation conditions, for the 0.5 MW unit an efficiency of 1.6% and for the 50 MW unit an efficiency of 2.5% were estimated [72].

As the next step for using the thermal energy stored in the Iranian bodies of water, first of all based on experimental data, the profile of water temperature versus depth for different sites should be measured and then some small scale plants should be constructed and monitored to assess the detailed information for full scale units.

5. Ocean current energy

Ocean currents are considered to be a form of indirect solar energy, because they are generated by wind and temperature differences in oceans due to solar heating. The Gulf Stream and Florida Straits Current are a few examples of the ocean current. It is estimated that global current power is 5×10^6 MW with power densities of up to 15 kW/m^2 [73].

In this approach, the ocean currents are used to move turbines. The turbines are usually installed in the flow path, so they do not need any dam. Similar to the tidal stream generators, these systems, in principle, are similar to wind turbines. However, the ocean current power has two major advantages over tidal current power, namely relatively constant flow and one directional flow. Laboratory tests have proven that this technology is feasible [73].

However, the Caspian Sea is a closed body of water and the Persian Gulf and Gulf of Oman are only connected to the ocean at one end. Therefore, none of the major ocean currents are considerable in these bodies of water [6], and so this energy cannot be obtained from the Iranian water.

6. Salinity gradient energy

In this scheme, the osmotic pressure difference between fresh and salty water, equivalent to 240 m of hydraulic head, is used to produce energy. It is reported that this concept has the highest energy density among marine based power resources [74]. Also in another approach, the different rate of evaporation of fresh and salty water can be used to move a low pressure turbine [75]. It is estimated that total power generation potential of this resource is around 2.6×10^6 MW. Although the high cost is an obstacle, the feasibility of these systems has been confirmed in laboratory conditions. In addition, there have been considerable developments in their commercial application due to the introduction of new less expensive and cost effective membranes to the market [74]. In order to employ the salinity gradient energy, water with very high salinity density as well as fresh water is required.

Although plenty of fresh water is available along the coast of the Caspian Sea, due to the very low water salinity, around 13 g/l [6], this system is not feasible in this sea. Similarly, in the Persian Gulf and Gulf of Oman with relatively low salinity density of around 48 and 37 g/l, respectively [6], using this approach does not seem practical.

On the other hand, Urmia Lake, with the salinity of 280 g/l in summer and 260 g/l in winter [6], is one of the saltiest bodies of water in the world. Furthermore, it has some fresh water rivers that spill into it. Therefore, it is an ideal site to obtain the salinity gradient energy.

7. Conclusions

Iran has a great potential to use sea/ocean renewable energies. The potential energies of each body of water in Iran can be categorized as follows.

7.1. The Persian Gulf and Gulf of Oman

The Gulf of Oman is connected to the Indian Ocean and there is a maximum potential of 12.6 kW/m power in its waves. But in the Persian Gulf's coasts, due to their distance from the ocean, the wave power potential is at most 6.1 kW/m. However, in the Persian Gulf islands, there is a great source of energy (maximum 19 kW/m and average 16.6 kW/m). These isolated islands are the best places to exploit the wave energy.

For tidal energy, owing to strong tides in the southern coastal region of Iran, there are many suitable sites. Among 36 sites which have been studied, Mahshahr port with 3.9 m tidal range and 170 km^2 basin area is the best one.

As far as the thermal energy is concerned, although the Persian Gulf is one of the hottest seas in the Middle East and its surface temperature is about 30 °C in August, due to the depth of this sea, which is about 30–182 m, the required cold water to be obtained from the depths is not available. Salinity gradient and current energies are not sufficient to be practical in these bodies of water.

7.2. The Caspian Sea

Since the Caspian Sea is a closed body of water, neither the wave nor the tidal energy is considerably high and they are not suitable for energy production.

But the Caspian Sea is suitable to harness the sea thermal energy. In this sea, the temperature difference between surface and deep water is about 20 °C during 7–8 months of the year. Also, the deepest point of the sea is located in its southern Persian side and the distance of the iso-depth lines of 300–400 m does not exceed 20 km from the Iranian coasts. There are also few storms in this sea.

7.3. Urmia Lake

Urmia Lake, having a salinity of more than 260 g/l throughout the year, is one of the saltiest bodies of water in the world. It also has some fresh water that spills into it. Therefore, it is an ideal site for the salinity gradient energy.

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